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Technical Report

Contributions

to

AFOSR-89-0226A (Wall Layers)

and

Current Research Directions

15 January 1989-14 January 1990

James M. McMichael, Program Manager

Principal Investigators
John L. Lumley
Sidney Leibovich
Philip Holmes
John Guckenheimer

Narrative

Philip Holmes is continuing to study the mathematical foundations of our general approach to the turbulent boundary layer: projection of the Navier-Stokes equations onto (relatively) low dimensional subspaces spanned by empirical eigenfunctions. In particular, in a brief paper prepared for the ICM '90 Proceedings (Kyoto, Japan), Berkooz, Holmes and Lumley show that, on the average, the coupling terms between resolved modes lacking streamwise variation and unresolved nodes cannot transfer energy from the latter to the former, even if relatively low wavenumbers are among the latter, neglected modes. Holmes also continued his study of symmetry-induced heteroclinic cycles, their relation to the bursting process (and more generally to intermittency in turbulence production) and their behavior in the presence of multiple local and global instabilities in phase space.

Peter Swart is currently investigating (with P. Holmes), the large-time behavior of systems that can develop fine structure. In particular they are looking at some visco-elastic models relevant to structural phase transitions - for these investigations they have just been awarded supercomputer resources by the NSF supercomputer - allocations committee.

Swart received an MSI Graduate Fellowship for the academic year 1990-91.

During the past nine months Mark Myers has primarily provided technical support for the development of the **kaos** dynamical system toolkit, developed by Drs. Guckenheimer and Kim. During this period several parts of the program were enhanced, a delivery version of the package was generated and a users' guide was prepared. The addition of new code to the program in the fall was substantial; for example, a complete conversion of the eigenvalue and eigenvector computation routines in the EISPACK library from FORTRAN into the C language was performed so that these well-established algorithms could be included in **kaos**. Since the **kaos** package was made publicly available in February, a number of error reports have been received and appropriate action taken by various members of the **kaos** support group. It is expected that continued support of this kind for the **kaos** package will be required in the future.

Concurrent with the **kaos** development work, the Applied Mathematics computing center facilities were greatly enhanced and support by the research grant allowed Myers to participate in this expansion. The center currently supports seven Sun workstations available for use by faculty and students, two of which were purchased by our group. These computers are used frequently by members of the turbulence research group; system support and maintenance is crucial if we are to insure that the group continues to benefit from these resources.

Sidney Leibovich was elected Chairman of the U.S. National Committee on Theoretical and Applied Mechanics (A committee of the NRC and Nat. Academies), 1990-92. He was also elected U.S. Delegate to the IUTAM.

Sue Campbell (in collaboration with Phil Holmes) is just finishing up work on the interactions between structurally stable heteroclinic cycles and travelling waves in a three mode truncation (modes 1, 2 and 4) of the model studied by Aubry et al.; they have a paper ready for submission entitled "Bifurcation from symmetric heteroclinic cycles with three interacting modes".

The purpose of this work was to better understand the heteroclinic behavior seen in the many-mode models by Aubry et al., which is thought to be related to the bursting phenomenon observed in turbulence. As the heteroclinic cycles often appeared between fixed points in the 2:4 subspace of the larger systems, it was apparent that in order to understand the behavior in the larger systems one must first understand the dynamics in this subspace.

The 1:2:4 mode system was chosen to be studied in the hope that it would be large enough to retain much of the behavior in the larger systems, but small enough to be tackled analytically. The former was certainly true, for much rich behavior reminiscent of that seen in the higher-mode models was observed through numerical experiments. The latter was somewhat true, and with the aid of MACSYMA some results on the existence of the heteroclinic cycles and their bifurcation to modulated travelling waves were established.

Andrew Poje is currently working (with John Lumley) on the eduction of coherent structures in wall bounded flows by analytical methods. This work is taking place in a two pronged fashion. The problem as originally formulated by Lumley (1969) has been solved numerically for both channel and open boundary layer flow. An extensive data set is available for the calculation of coefficients in the dynamical systems derived by Aubry et al. (1987). A study of the dynamics of systems formed using analytic eigenfunctions, and a comparison with and extensions to the work of Aubry et al., is currently taking place. Along these lines, the recent acquisition of a large set of Proper Orthogonal Decomposition eigenstructures from DNS data of Kim and Moin allows for direct comparison of POD and linear energy eduction techniques. Preliminary results of the scaling behavior of the energy content of structures derived by both methods is available in a note being composed by Berkooz and Poje (see below).

Poje is also pursuing another aspect of linear energy-method stability analysis; this focuses on extensions of the technique to more complicated flows. A simple model for the effects of riblets on the growth and form of eigenstructures is under investigation. This model is a straight-forward extension of previous work to flows with mean profiles that depend on both wall-normal and spanwise coordinates. A more complicated extension of the eduction method to the case of the thermal boundary layer is under investigation. This flow, with applications to boundary layer control, is of acute meteorological interest. It is hoped that the relatively simple eduction method under consideration will allow the application of dynamical system techniques to models of the atmospheric boundary layer.

Scott Jones (in collaboration with Leibovich) is currently investigating shear dispersion by chaotic advection. He has performed preliminary calculations of the stirring of fluid particles in a flow composed of a superposition of a second order irrotational wave solution plus a linear shear. He has demonstrated that this flow can generate chaotic particle trajectories. Starting with particles initially configured as a circle, the flow given by a two-mode approximation plus shear causes exponential growth in a measure of particle separation.

Jones and Leibovich are also applying the ideas from Langmuir circulation to the wall region of a turbulent channel flow. This is done using the Generalized Lagrangian Mean formulation. Lumley and Leibovich have concluded that the wall region of a turbulent channel flow or boundary layer is very similar to the ocean surface mixed layer, but upside down. The turbulent fluctuations in the wall region generate a pseudo-momentum (related distantly to the Stokes drift) just as the surface gravity wave motions do in the ocean surface mixed layer. We expect the same sort of instability, by the same mechanism (stretching of perturbed cross-stream vorticity by shear in the Stokes drift), leading to longitudinal rolls in both cases. We identify these rolls as the coherent structures observed in the wall region, and implicated in the bursting process. Lumley has generated approximate forms for the pseudo-momentum in the wall region, using data from the measurements of Favre *et al*. These forms will be used in calculations of the genesis of the rolls.

Stephen M.Cox is also working on Langmuir circulations, but in a stratified ocean, with Sidney Leibovich. They are looking at the possibility of modeling the slow and long-wavelength modulations of the amplitudes of the rolls by using coupled Ginzburg-Landau-type equations. This sort of analysis can also be applied to the slow and long-wavelength modulations of the amplitude of rolls in the wall region of the turbulent boundary layer.

Cox is also collaborating with John Guckenheimer on the interaction of parametrically excited surface waves in a nearly square container subject to vertical oscillations. They are trying to make sense of apparent disagreements between weakly non-linear theory and experimental evidence. The equations describing this system have many points of similarity with the equations describing the wall region of a turbulent flow, but are in some respects more tractable. It is expected that insight gained in one system will carry over to the other.

Gal Berkooz has given primary attention during this report period to understanding and explaining the behavior exhibited by the low dimensional dynamical systems studied in Aubry et al., in particular in light of Moffat's observations (in *Whither Turbulence?*). Moffat pointed out that streamwise rolls without streamwise variation decay according to the exact equations, whereas in our model system they are able to maintain themselves. To this end Berkooz did the following:

He showed that the notion of coupled and uncoupled systems of equations is not determined by the form of the equations alone, but is also dependent on the norm defined on the space in which one is working. This is the "mathematical" observation which answers Moffat's criticism.

He collaborated with J.L. Lumley and P.Holmes in showing that the bursting behavior displayed by the low dimensional model system is not an artifact of the coupling introduced by the modeling, but persists in an uncoupled (decaying) system They also showed that the production of energy in these systems is within the experimentally observed values for the modes used in the truncation.

Berkooz also showed that several assumptions made on an intuitive basis in the work of Aubry et al. may be justified formally. Namely:

That the Heisenberg model used gives the correct dissipation to within a factor of order unity, as assumed.

That the Leonard stresses may be neglected in the case of modeling with no streamwise variation, as assumed.

That the previous result holds for an arbitrary number of eigenfunctions when no streamwise variations are present.

Berkooz gave a physical meaning to the notion of models with no streamwise variation and showed that in effect they average the streamwise dynamics, as conjectured by Holmes.

Berkooz also applied dynamical systems models to the control of the turbulent boundary layer. As observed by Lumley, the dynamical systems models are the only mechanistic description of the dynamics in the wall region of the turbulent boundary layer, and as such are the only candidates for establishing a smart control scheme. Early work of Marsden and Bloch showed that systems with homoclinic attractors are in principal controllable, with a certain type of control input. Berkooz's efforts in this direction were concentrated on determining the feasibility of the control and trying to understand the possible gains in terms of drag reduction or mixing enhancement. To this end he did the following:

He introduced the notion of short term tracking time (denote T_s). This is a time scale characteristic of the time over which the dynamical system model tracks the true dynamics accurately. T_s is of fundamental importance in the control application; it must be of the order of the wall region time scales to enable control.

Berkooz showed that dynamical systems based on the Proper Orthogonal Decomposition have, on the average, the best T_s for a given number of modes.

To determine the effect of control actuators on the structure of the turbulent boundary layer, Berkooz suggested a numerical scheme for a direct pseudo-spectral numerical simulation . Work is currently in progress in implementing this scheme, with D. Bond.

Berkooz also submitted a proposal to the Center for Turbulence Research summer session for determining T_s based on their D.N.S. data. The proposal was accepted and hopefully the work will take place in the summer of '90.

Berkooz also generalized previous work, turning the dynamical systems approach to a quantitative predictor, among other pertinent topics. To this end he did:

He generalized the work of Armbruster, Guckenheimer and Holmes concerning the structural stability of heteroclinic connections in systems with O(2) symmetry to three complex dimensions, supporting the conjecture that the previously established results are generalizable to higher dimensions.

He recognized that to get quantitative predictions will require generating higher and higher dimensional dynamical systems, and that the best way to go about this is to utilize computer algebra. To this end he initiated an interdisciplinary effort to meet this requirement. Participants include Professors R. Zippel from Computer Science, S. Rapkin of Computer Science and Y.Y. Du of Applied Math.

He collaborated with A. Poje in studying the asymptotic behaviour of empirical eigenvalues and energy stability eigenvalues. This is required if one wants to assign energy content to stability analysis eigenfunctions in an internally consistent manner. This, in turn, is essential for utilizing stability analysis eigenfunctions instead of empirical eigenfunctions in dynamical systems models.

The 1982 experiment by Hopfinger, Browand and Gagne (HBG; *JFM* **125**: 505-534) displayed remarkable self-organization of turbulent flows in a rotating tank. The turbulent flows form well-ordered patterns consisting of very strong concentrated vortices running the length of the tank, parallel to the angular velocity vector. To understand this pattern formation process, which has implications for all flows in which vorticity of several scales is present, Guang Yang (in collaboration with S. Leibovich) is planning a direct numerical simulation of the flow between two infinite parallel planes with boundary forcing at one plane. The Navier-Stokes equations are solved using a pseudo-spectral method.

The code for the numerical simulation has been written. Its accuracy has been checked by computing the evolution of small and finite-amplitude two-dimensional disturbances of plane Poiseuille flow and comparing the results with their predicted behavior according to the Orr-Sommerfeld equation and the numerical simulation results of Orszag and Kell (*JFM* **96**: 159-205). Now Yang and Leibovich will simulate the HBG experiment, but at a Reynolds number lower than that in the experiment.

In the course of the 1989-1990 academic year, Jerrold Marsden decided not to accept a permanent position at Cornell, but to return to UC Berkeley, from which he was on Leave of Absence. We have not yet decided how to restructure the research program. Marsden has already made a definitive contribution, and we would probably be able to proceed without further input in his area. We could continue to work with him at Berkeley, or we could take on someone else in the control area, either at Cornell, or elsewhere. We are seriously considering taking on Anthony Bloch (who did the earlier control work under Marsden's direction) as a consultant. Bloch is now at Ohio state. Electronic communication is now such that this would not present a problem.

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Current Research Directions

15 January 1990-14 January 1991

James M. McMichael, Program Manager

Principal Investigators
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Sidney Leibovich
Philip Holmes
John Guckenheimer

Research synopsis

Current research efforts of Poje and Lumley are focused on accurately (adequately) modelling the effects of modulated Reynolds stresses on the form of the coherent structures predicted by an energy maximization principle. We have found that a simple eddy-viscosity relation does not adequately model the stresses which may act as production terms for the coherent structures. An anisotropic eddy-viscosity tensor has been derived from second order equations by assuming the coherent velocity field to be an order epsilon perturbation to the mean field. Initial results using this model show coherent structures which are quite similar to those predicted by the Proper Orthogonal Decomposition.

J. Elezgaray gave a mini-course on wavelets during the fall semester. The course was intended for people interested in applications such as the turbulent boundary layer. The course consisted of five lectures, for which lecture notes are available.

So far our decompositions have used Fourier modes in the homogeneous spanwise and streamwise directions. These distributed functions, while energy-optimal on average, are not well adapted to reproduce spatially localized events such as bursts. In addition, one of the points on which the work of Aubry *et al* was criticised, was that the structures produced were not localized in space like the structures observed in the turbulent boundary layer. Wavelet bases, having compact support, seem much more appropriate. J. Elezgaray is currently studying, jointly with G. Berkooz and P. Holmes, applications of wavelets to the study of coherent structures arising from the Kuramoto-Sivashinsky equation. This study is preliminary to a more involved study of the more complex turbulent boundary layer, permitting us to gain experience with the application of wavelets in chaotic systems.

Berkooz, in collaboration with Holmes and Lumley, gave substantial attention to understanding and explaining the behavior exhibited by the low dimensional dynamical systems studied in Aubry *et al.* In particular, they showed that several assumptions made on an intuitive basis in the work of Aubry *et al* may be justified formally, namely: that the Heisenberg model used gives the correct dissipation within a constant of order unity, as assumed; that the Leonard stresses may be neglected in the case of modeling with no streamwise variation, as assumed; that the previous result holds for an arbitrary number of eigenfunctions when no streamwise variation is present; that models with no streamwise variation in effect average the streamwise dynamics, as conjectured by Holmes.

Berkooz, Lumley and Holmes submitted a proposal to the Center For Turbulence Research summer session for determining the short term tracking time (T_s) from the CTR's data from direct numerical simulation for channel flow. The proposal was accepted, and the following work took place during the 1990 summer session: the DNS data sets for the "minimal flow unit of wall turbulence", studied by Jiminez and Moin, were examined in detail. The minimal flow unit is the smallest computational domain found to sustain a velocity field similar (in some statistical characteristics) to a turbulent field. It was decided to use this data set since it shares some key features with the dynamical systems models; it was also considerably simpler to access than the full channel simulations. The time traces were produced, for what would correspond to the eigenfunction coefficients. These were produced with the idea of measuring T_s, but this proved to be too involved for the time available. A qualitative numerical evaluation of the predictions based on the dynamical systems approach was carried out. The main contribution of this work was to establish a methodology for the evaluation of dynamical systems, and to introduce some new concepts. The amount of data was insufficient to permit decisive conclusions.

Lumley has pointed out that the dynamical systems models are the only mechanistic description of the dynamics of the wall region of the turbulent boundary layer, and thus are the only candidates for establishing a smart control scheme. Early work of Marsden and Bloch showed that systems with homoclinic attractors are in principle controllable, with a certain type of control input. Our efforts in this direction are concentrated on determining the feasability of control, and trying to understand the possible gains in terms of drag reduction and mixing enhancement. To this end Berkooz, Holmes and Lumley introduced the notion of short term tracking time T_s. This is a measure of the time over which a dynamical systems model tracks the true dynamics accurately. T_s is of fundamental importance in the control application, and it must be of the order of the wall-region time scales to make control possible. They then showed that dynamical systems based on the Proper Orthogonal Decomposition have, on the average, the best T_s for a given number of modes.

To determine the effect of control actuators on the structure of the turbulent boundary layer, Berkooz, Holmes and Lumley suggested a numerical scheme for a direct (pseudospectral) numerical simulation scheme. This year David Bond and Berkooz studied the DNS channel code of Moin, Kim & Moser from CTR, and translated it into FORTRAN so that it could be run locally. An algorithm was formulated for implementation of a linearized boundary condition simulating the flow over a control actuator. The group applied for, and received, 200m Cray hours on the NAS system (at NASA/Ames) for the implementation of the numerical scheme.

Berkooz generalized the work of Armbruster, Guckenheimer and Holmes regarding the structural stability of heteroclinic connections in systems with O(2) symmetry to three complex dimensions, supporting the conjecture that the previously established results are generalizable to higher dimensions. This is related to the work of Campbell and Holmes (see below).

Berkooz recognized that to get quantitative predictions will require generating higher and higher dimensional dynamical systems, and that the best way to go about this is to utilize computer algebra. To this end, Berkooz initiated an interdisciplinary effort involving R. Zippel and S. Rapkin from Computer Sciences.

Berkooz collaborated with A. Poje in studying the asymptotic behavior of empirical eigenvalues and energy stability eigenvalues. This is required if one wants to assign energy content to stability analysis eigenfunctions in an internally consistent manner. This, in turn, is essential for utilizing stability analysis eigenfunctions instead of empirical eigenfunctions in dynamical systems models.

Berkooz studied the mathematical properties of the proper orthogonal decomposition and the phenomena of localized coherent structures in homogeneous (statistically translation invariant) systems. He established some results of particular interest in our context, regarding mathematical properties of the POD.

Guckenheimer's work is continuing on computational tools for exploring dynamical systems. They are developing a window interface that can be used to control computations on a work station or remote machine - with the goal of using powerful parallel processors as computational engines.

Mahalov and Guckenheimer have extended the work of Armbruster, Guckenheimer and Holmes on structurally stable homoclinic cycles to three-wave interactions in systems with symmetry.

Berkooz has made rigorous estimates using the proper orthogonal decomposition showing that a structured turbulent flow, such as the wall layer, has a phase space representation that remains within a thin slab centered on the most energetic modes for most of the time. However, exits from this region, which is all that our low-dimensional models include, should not be ignored, since they typically correspond to violent events, such as the bursting phenomenon. Berkooz and Holmes are trying to develop a theory in which deterministic, low-dimensional dynamics governing the low modes applies most of the time, passages from and returns to this being modeled probabilistically. This might be viewed as a dynamical closure. They plan to test their theory on problems including the 32 and 54 dimensional projections of Aubry and Sanghi.

Sue Campbell and Phil Holmes are continuing their studies of symmetry breaking ($O(2) \rightarrow D4$) in systems with structurally stable heteroclinic cycles. They have proved that no analytic (second) integral of motion exists in a certain limiting case and that only two pairs of the continuum of O(2) symmetric heteroclinic cycles persist in general. They are studying the bifurcations from these survivors. This work is relevant to our models of interacting coherent structures in boundary layers with discrete spanwise symmetry, such as that caused by riblets. This is to our knowledge the first analytical contribution to our understanding of the drag reduction caused by riblets.

Pieter Swart and Phil Holmes are studying the dynamic anti-plane shear problem for nonlinear viscoelasticity with change of type. Three numerical codes (finite difference, spectral and wavelet based) have been written and are currently being tested. Theoretical studies of the equations, using Rybka & Kohn's generalization of the Andrews-Ball-Pego transformation, also continue. Although the problem itself is only of remote interest to the subject of this contract, the relative performance of the three types of codes is definitely of interest.

With Scott Jones, Sid Leibovich is working on a generalized Lagrangian Mean decomposition of channel flow. They are first trying the decomposition on finite amplitude, 2D Tollmien-Schlichting waves, and then will move to turbulent channel flow. The velocity fields are generated by a DNS code developed by G. Yang.

Leibovich and Lumley proposed the application of the averaging procedure known as the Generalized Lagrangian Mean to the fully turbulent boundary layer problem. With John Lumley, Sid Leibovich is developing a modelled set of equations for the Generalized Lagrangian Mean of turbulent wall layers. Leibovich and Mahalov plan to extract coherent structures from the averaged equations. The next step would be to study resonances between these averaged structures. Their preliminary estimates show that the coupling coefficients in the equations describing interaction of average structures are adiabatic invariants, and are therefore important characteristics of the turbulent flow. They also hope to be able to show that heteroclinic cycles are present in the averaged equations; these are identified with the bursting events in the boundary layer. Mathematical work has been started in this direction.

Leibovich and Mahalov have been studying rotating pipe flow. While this is remote from the subject of this contract, the techniques developed have application to the boundary layer (see below). Specifically, they studied interactions of distinct families of 2-D helical waves, and found a mechanism, resonant triad interaction, for the interaction of these waves resulting in fully three-dimensional flows.

Recently Corke & Mangano, and Kachanov have published new data on transition in boundary layers. It appears that resonant triad interactions of Tollmein-Schlichting waves play a major role here. Leibovich and Mahalov feel that they will be able to explain many of the results using techniques and methods developed for rotating pipe flow. One of their goals is to explain and analyze the spikes observed in these experiments. They have proposed that the doubling and tripling of spikes may be due to the splitting of a wave into solitons, a phenomenon observed in other equations. They intend to use a wavelet basis to analyze this problem, and are working with J. Elezgaray to develop the technique.

With G. Yang, Sid Leibovich is attempting a direct numerical simulation of turbulence generated by an oscillating grid in rotating flows.

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Berkooz, G. 1990. A numerical evaluation of the dynamical systems approach to wall-layer turbulence. *Proceedings*, 1990 Summer Session. Palo Alto, CA: The Center for Turbulence Research.

Berkooz, G. Guckenheimer, J., Holmes, P., Lumley, J.L., Marsden, J., Aubry, N. & Stone, E. 1990 Dynamical-systems-theory approach to the wall region. AIAA Paper No. 90-1639.

Brown, S. N., Leibovich, S., & Yang, Z. 1990. On the linear instability of the Hall-Stewartson vortex. *Theoretical and Computational Fluid Dynamics* 2: 27-46.

Ettestad, D.J. & Lumley, J.L. 1989. A Correction Term for the Swirling Jet. In *Mathl. Comput. Modelling*. Vol. 12 No. 12, pp. 1583-1588.

Ettestad, D.J. & Lumley, J.L. 1989. Modelling the Dissipation Transport Term. In *Math. Comput. Modelling*. Vol. 12 No. 7, pp. 865-869.

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Kim, S. & Guckenheimer, J. 1990. The two dimensional torus: numerical explorations and mathematical conjectures. *Chaos/XAOC Soviet-American Perspectives on Nonlinear Science*, pp. 145-152. New York: AIP.

Kribus, A., & Leibovich, S. 1990. Large amplitude wavetrains and solitary waves in vortices. *J. Fluid Mech.* 216: 459-504.

Leibovich, S. 1990 Vortex breakdown: a coherent transition trigger in concentrated vortices. In *Organized structures and turbulence in fluid mechanics*, eds. M. Lesieur & O Métais. Holland: Kluwer.

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Stone, E. & Holmes, P. 1990. Random perturbations of heteroclinic attractors. *SIAM J on Applied Math*, 50: 726-743.

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Baesens, C., Guckenheimer, J., Kim, S & MacKay, R. 1990. Three coupled oscillators: mode-locking, global bifurcations and toroidal chaos. *Physica D*, In press.

Baesens, C., Guckenheimer, J., Kim, S. & MacKay, R., 1990. Simple resonance regions of torus diffeomorphisms, *Proceedings*, IMA Workshop on Chemical Reactors. To appear.

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Leibovich, S. 1990. Structural genesis in wall-bounded turbulent flows. In *The Lumley Symposium: Recent Developments in Turbulence*, eds. T. Gatski & C. Speziale. Berlin etc.: Springer. To appear.

Lumley, J. L. 1990. Some comments on turbulence. *J. Fluid Mechanics*. Submitted.

Mahalov, A. & Leibovich, S. 1990. Multiple bifurcations of rotating pipe flow. *Theo. Comp. Fluid Mech.* Submitted.

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Panchapakesan, N. R. & Lumley, J. L. 1990. Turbulence measurements in an axisymmetric jet of air. *J. Fluid Mech.* Submitted.

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Stone, E. & Holmes, P. 1990. Unstable fixed points, homoclinic orbits and exponential tails. *Phys. Lett. A* Submitted.

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Akutowicz, A. A. 1990. A study of source terms in the pressure equation in a high speed flow with entropy fluctuations. Sibley School of Mechanical and Aerospace Engineering Report No. FDA-90-05. Ithaca, NY: Cornell.

Armbruster, D., Guckenheimer, J. & Kim, S. 1990. Resonant surface waves in a square container. In manuscript.

Berkooz, G. & Poje, A. 1990. Scaling of energy content of coherent structures in turbulence. In manuscript.

Berkooz, G. 1990. Higher dimensional systems with O(2) symmetry. In manuscript.

Berkooz, G., Elezgaray, J. & Holmes, P. 1990. Use of wavelets in study of coherent structures in the Kuramoto-Sivashinsky equation. In preparation.

Guckenheimer, J. & Johnson, S. 1990. Beyond hyperbolicity: expansion properties of one-dimensional mappings. In manuscript.

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Leibovich, S. & Mahalov, A. 1991. Spatio-temporal dynamics in Hagen-Poiseuille Problem. In preparation.

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Poje, A. C. 1990. *Eduction of coherent structures in the turbulent near-wall region via energy methods*. Sibley School of Mechanical and Aerospace Engineering Report FDA-90-07. Ithaca, NY: Cornell.

Outside lectures

Berkooz, G. A numerical evaluation of the dynamical systems approach to wall-layer turbulence. 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990. (*Bull. APS* 35:2266 DA2).

Berkooz, G. A numerical evaluation of the dynamical systems approach to wall-layer turbulence. Center for Turbulence Research, Summer, 1990.

Berkooz, G. Dynamical systems model for the wall region of a turbulent boundary layer. NASA/LaRC August 1990.

Berkooz, G. Observations on the proper orthogonal decomposition. Dynamics seminar, Center for Applied Mathematics, Cornell. Fall, 1990.

Berkooz, G. Observations on the proper orthogonal decomposition. The Lumley Symposium: Recent Developments in Turbulence. NASA/ICASE, Langley Research Center, November 12-13, 1990.

Elezgaray, J. Application of wavelets to the study of coherent structures in the Kuramoto-Sivashinsky equation. Wall Layers Research Group meeting, Cornell. Fall, 1990.

Holmes, P. J. & Stone, E. Heteroclinic cycles, exponential tails and intermittency in turbulence production. The Lumley Symposium: Recent Developments in Turbulence. NASA/ICASE, Langley Research Center, November 12-13, 1990.

Holmes, P. J. A mathematical cartoon for the dynamics of fine structure. 8th Army conference on applied mathematics and computing. Ithaca, NY, June 19-22, 1990.

Holmes, P. J. An evolution equation with everything to lose but nowhere to go. Courant Institute, New York University, November 5, 1990.

Holmes, P. J. An evolution equation with everything to lose but nowhere to go. Dynamics Days Texas, Houston, TX January 6-9, 1991.

Holmes, P. J. Can dynamical systems approach turbulence? Heriot Watt University, Edinburgh, Scotland, UK. March 12, 1990.

Holmes, P. J. Can dynamical systems approach turbulence? International congress of mathematicians, Kyoto, Japan. Invited sectional lecture (one of only three in Applied Math. section). August 21-29, 1990.

Holmes, P. J. From nonlinear oscillations to horseshoes and on to turbulence, perhaps. Smalefest, Berkeley, CA, August 5-9, 1990.

Holmes, P. J. Intermittency and symmetric heteroclinic cycles in weak turbulence. DAMTP, Cambridge University, UK, March 9, 1990.

Holmes, P. J. Intermittency in simple models of turbulence. Thomas J. Watson Research Center, IBM Yorktown Heights, NY. March 19, 1990.

Holmes, P. J. Low dimensional projections of a turbulent boundary layer. IMA Workshop on dynamical theories of turbulence in fluid flows, Minneapolis, MN, May 29-June 2, 1990.

Holmes, P. J. On the dynamics of fine structure. University of Pittsburgh/Carnegie Mellon Joint Applied Mathematics Colloquium, March 23, 1990.

Holmes, P. J. Symmetry, global dynamics and intermittency. Dept. of Mathematics, Kyoto University, Kyoto, Japan. August 23, 1990.

Holmes, P. J. Unstable fixed points, heteroclinic cycles and exponential tails in turbulence production. Levich Institute, CCNY, November 6, 1990.

Leibovich, S. Hopf bifurcations with O(2) symmetry in Langmuir circulations (with S,. M, Cox & I. M. Moroz). 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990. (*Bull. APS* 35:2326).

Leibovich, S. Local dynamics of vortical flows. IUTAM Symposium on separated flows and jets. Novosibirsk, July 9-13, 1990. (Invited plenary lecture).

Leibovich, S. Nonlinear evolution of marginally unstable wave packets in rotating pipe flow (with Z. Yang). 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990. (*Bull. APS* 35:2235).

Leibovich, S. Structural genesis in wall-bounded turbulent flows. The Lumley Symposium: Recent Developments in Turbulence. NASA/ICASE, Langley Research Center, November 12-13, 1990.

Lumley, J. Fundamental directions for experimental turbulence research. In New approaches to experimental turbulence reserach, Princeton, September 5-7, 1990. Inviteed paper.

Lumley, J. L. Control of the boundary layer and dynamical systems theory: an update (with Berkooz, G., Holmes, P.) In *The Global Geometry of Turbulence*, Rota (Cádiz, Spain), July 8-14, 1990.

Lumley, J. L. Measurements in a circular jet of helium into air. NASA Lewis Research Center. June 4, 1990. Invited seminar.

Lumley, J. L. Panel discussion: is this the theory for these experiments? In *The Global Geometry of Turbulence*, Rota (Cádiz, Spain), July 8-14, 1990.

Lumley, J. L. Some comments on turbulence. APS Fluid Dynamics Prize Lecture, 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990.

Mahalov, A. & Leibovich, S. Helical bifurcations and resonant triad interactiojns in the rotating Hagen-Poiseuille problem. IUTAM Symposium on nonlinear hydrodynamic stability and transition, Univ. of Nice, September 3-7, 1990. (Invited paper).

Mahalov, A. & Leibovich, S. Resonant Tollmein-Schlichting triad interactions in channels. 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990. (*Bull. APS* 35:2264).

Poje, A. C. & Lumley, J. L. Analytic extraction of coherent structures. 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990. (*Bull. APS* 35:2315. IB2).

Ristorcelli, J. R. & Lumley, J. L. Second order turbulence simulation of buoyantly driven recirculating flow with swirl. 43rd Annual meeting, Division of Fluid Dynamics, American Physical Society, Ithaca, NY Nov. 18-20, 1990. (*Bull. APS* 35:2286 FC6).

Ristorcelli, J. R., Jr. & Lumley, J. L. Turbulence in the Czochralski crystal melt. ICHMT XX Materials Processing Symposium, Dubrovnik, Yugoslavia. August, 1990.

Awards, honors, new responsibilities

Holmes, P. Member of Comité Consultatif, Centre de Recherches Mathématiques, Université de Montréal.

Holmes, P. Member of Nonlinear Systems Panel, Science & Engineering Research Council (UK).

Leibovich, S. Elected Chairman, U. S. National Committee on Theoretical and Applied Mechanics (3 year term).

Leibovich, S. US delegate to the IUTAM General Assembly, Vienna, August 1990.

Lumley, J. L. Editor and Chairman, Editorial Committee, Subcommittee on Research Directions in Fluid Mechanics, U. S. National Committee, Theoretical and Applied Mechanics.

Lumley, J. L. Fluid Dynamics Prize, American Physical Society. November, 1990.

Lumley, J. L. Member, Advisory Committee, 8th Turbulent Shear Flows Symposium.

Lumley, J. L. Member, International Scientific Committee, Symposium on Interpretation of Time Series from Mechanical Systems, University of Warwick, England, 25-30 August, 1991.

Lumley, J. L. Member, Scientific Committee, IUTAM Symposium Eddy Structure Identification in Free Turbulent Shear Flows, Poitiers, France, September 14-16, 1992.

Lumley, J. L. The Lumley Symposium: Recent Developments in Turbulence. Held at NASA Langley in honor of Lumley's 60th Birthday. November 12-13, 1990.

Lumley, J. L. Chairman, Ad-Hoc Planning and Advocacy Group for Turbulence.

Professional activities

Guckenheimer, J. Board of Editors, *Physics D.*

Guckenheimer, J. Advisory Committee, European Science Foundation Network on Nonlinear Science.

Guckenheimer, J. Advisory Committee, Mathematical Sciences Institute.

Guckenheimer, J. Board of Editors, *SIAM Review.*

Guckenheimer, J. Director, Center for Applied Mathematics, Cornell University.

Holmes, P. Editorial Board member, *Archive for Rational Mechanics and Analysis.*

Holmes, P. Editorial Board Member, *Journal of Nonlinear Science.*

Holmes, P. Editor in Chief, *Nonlinear Scinece Today.*

Holmes, P. Reviewer for *Physica D, J. Sound Vib., J. Phys., Q. Appl. Math, Phys. Fluids, J. Fluid Mech., Europhys. Lett., Ergodic Theory and Dynamical Systems, Phys. Lett. A.*

Leibovich, S. Associate Editor, *J. Fluid Mech.*

Leibovich, S. Chairman, Operations Committee, Basic Engineering Group Operating Board, ASME.

Leibovich, S. Co-editor, *Acta Mechanica*

Leibovich, S. Member, Congress Committee of the International Union of Theoretical and Applied Mechanics, 1988-1992.

Leibovich, S. Member, editorial board, Annual Reviews of Fluid Mechanics 1989-1994.

Leibovich, S. Member, Scientific Committee, 2nd International Conference on Fluid Mechanics, Beijing, July 1992.

Leibovich, S. Member, Timoshenko Medal Selection Committee, ASME.

Leibovich, S. Member-at-Large, Basic Engineering Group Operating Board, ASME.

Leibovich, S. Member-at-Large, U., S. National Committee of Theoretical and Applied Mechanics, 1988-1992.

Leibovich, S. Past chairman and member, Executive Committee, Division of Fluid Dynamics, American Physical Society.

Leibovich, S. Reviewer: *J. Fluid Mech., Phys. Fluids, J. Phys. Oceanogr.* NSF.

Leibovich, S. Scientific Committee, 8th Symposium on Trends in Applications of Mathematics to Mechanics, Vienna, Auguat 13-18, 1989.

Leibovich, S. Scientific Committee, 11th US Congress of Theoretical and Applied Mechanics, Tucson, 1990.

Lumley, J. L. Chairman, Advisory Committee, Center for Turbulence Research, Stanford, NASA Ames.

Lumley, J. L. Chairman, Technical editorial board, *Izvestiya: Atmospheric and Oceanic Physics.*

Lumley, J. L. Co-editor, *Annual Reviews of Fluid Mechanics.*

Lumley, J. L. Conference General Chairman, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society. Ithaca, NY November 18-20, 1990.

Lumley, J. L. Editor, *Theoretical and Computational Fluid Dynamics.*

Lumley, J. L. Member, editorial board *Fluid Mechanics: Soviet Research.*

Lumley, J. L. Member, editorial board, *Probabilistic Engineering Mechanics.*

Lumley, J. L. Reviewer, *J. Fluid Mech., Phys. Fluids, Physics Letters A, Combustion Science & Technology, AIAA J, Int. J. of Multiphase Flow, J. Sci. Instrum.*, NSF, ARO

Lumley, J. L. Session Chairman, Session No. 25, AIAA Fluid Dynamics, Plasma Dynamics and Lasers Conference. Seattle, WA, June 18-20, 1990.

Technical Report

Contributions

to

AFOSR-89-0226A (Wall Layers)

and

Current Research Directions

15 January 1991-14 January 1992

James M. McMichael, Program Manager

Principal Investigators
John L. Lumley
Sidney Leibovich
Philip Holmes
John Guckenheimer

Research synopsis

Current research efforts of Poje and Lumley are focused on accurately (adequately) modelling the effects of modulated Reynolds stresses on the form of the coherent structures predicted by an energy maximization principle. Results from use of the anisotropic eddy viscosity model show coherent structures which are quite similar to those predicted by the Proper Orthogonal Decomposition. Initially, the eigenvalue spectrum for these coherent structures peaked at too low a wavenumber; inclusion of feedback between the mean velocity profile and the coherent structures moved the peak to the observed wavenumber. We are now extending this work to include buoyant heat transfer.

So far our decompositions have used Fourier modes in the homogeneous spanwise and streamwise directions. These distributed functions, while energy-optimal on average, are not well adapted to reproduce spatially localized events such as bursts. In addition, one of the points on which the work of Aubry *et al* was criticised, was that the structures produced were not localized in space like the structures observed in the turbulent boundary layer. Wavelet bases, having compact support, seem much more appropriate. J. Elezgaray is currently studying, jointly with G. Berkooz and P. Holmes, applications of wavelets to the study of coherent structures arising from the Kuramoto-Sivashinsky equation. This study is preliminary to a more involved study of the more complex turbulent boundary layer, permitting us to gain experience with the application of wavelets in chaotic systems. They have successfully modeled the wavelet-wavelet interactions, and have produced a low-dimensional wavelet model that mimics in many respects the behavior of the Kuramoto-Sivashinsky equation. I. Moroz and J. Lumley (in collaboration with Berkooz and Elezgaray) are working on the extension of this work to the Navier Stokes equation.

To determine the effect of control actuators on the structure of the turbulent boundary layer, Berkooz, Holmes and Lumley suggested a numerical scheme for a direct (pseudospectral) numerical simulation scheme. After extensive work on the scheme involving a linearized boundary condition, it was determined that it was computationally unfeasable, since the large values of velocity near the wall where the cell size is small resulted in unacceptable time step restrictions. A new, exact, conformal transformation (to a flat boundary) has been devised. We have ported the computation from the NAS facility at NASA Ames to the Cornell Supercomputing facility; the unmodified code is running on both the IBM 3090 and a cluster of RS 6000 machines, designed to exploit extreme parallelism.

Berkooz recognized that to get quantitative predictions will require generating higher and higher dimensional dynamical systems, and that the best way to go about this is to utilize computer algebra. To this end, Berkooz initiated an interdisciplinary effort involving R. Zippel and S. Rapkin from Computer Sciences. The program they have written is now capable of reproducing the work of Aubry *et al* automatically, carrying out the Galerkin projection, determining the coefficients, and writing a program for the solution of the ODE's. The work has reached such a stage, that a proposal for major support has been submitted to DARPA.

With Scott Jones, Sid Leibovich is working on a generalized Lagrangian Mean decomposition of channel flow. They are first trying the decomposition on finite amplitude, 2D Tollmien-Schlichting waves, and then will move to turbulent channel flow. The velocity fields are generated by a DNS code developed by G. Yang.

Leibovich and Lumley proposed the application of the averaging procedure known as the Generalized Lagrangian Mean to the fully turbulent boundary layer problem. With John Lumley, Sid Leibovich has developed a modelled set of equations for the Generalized Lagrangian Mean of turbulent wall layers. Wing Ma, working with Leibovich, has shown that, with a simple assumption, these equations will produce the turbulent mean velocity profile, as well as the laminar one. This is the first, lowest order, demonstration that these equations provide an alternate to Reynolds averaging. Ma and Leibovich are currently using the GLM formulation to describe the growth of Tollmein-Schlichting waves in the laminar boundary layer. This is a test of the GLM formulation, since the results are well-known and well-understood. When this has been satisfactorily resolved, Ma will move on to the turbulent boundary layer.

Lumley considered the interaction between two adjacent bursting events, or between an event induced by an actuator (in an effort to control the layer) and a bursting event. He obtained expressions for the coefficients in the low-dimensional model, as modified by the presence of the adjacent event. The primary difference in the coefficients is that the coefficient of the linear term, representing pressure drop and loss to the unresolved modes, becomes complex, causing the system to spiral in toward a fixed point, instead of falling directly toward it. Brianno Coller and Phil Holmes, starting from this idea, have developed a control algorithm for our simplified backbone system, rotating the system about the fixed point first one way and then the other (or, easier to visualize: rotating the principal axes back and forth) to keep the system heading toward the fixed point as long as possible. The system, of course, finally escapes from control, and is allowed to jump. This sort of control results in a very substantial delay in jumps, and an effective drag reduction by something like a factor of three. It is somewhat unrealistic, however, in that control in a real boundary layer could not be adjusted on an arbitrarily short time scale, since one is limited by the response time of the fluid field. We will look into this, and also develop a firm theoretical basis for what is presently an *ad-hoc* method.

Berkooz has developed a control scheme for a low-dimensional model of the Kuramoto-Sivashinski equation, reminiscent of our low-dimensional model for the turbulent wall layer. He uses a control actuator which is the analog of our bump on the wall. So far, the drag reduction achieved is of the order of that achievable by riblets in a real boundary layer. These are preliminary results, however, and we believe that we can do better.

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Leibovich, S. & Mahalov, A. 1991. Weakly nonlinear analysis of rotating Hagen-Poiseuille flow . *European J. Mech. B. (Fluids)* 10(2): 55-60.

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Leibovich, S. 1991. Structural genesis in wall-bounded turbulent flows. In *Studies in Turbulence*, T. Gatski, S. Sarkar & C. Speziale, eds., Springer-Verlag, 1991, pp. 387-411.

Lumley, J. L. 1991. Review of McComb, W. D. 1990 *The Physics of Fluid Turbulence*. Oxford, UK: Clarendon. 572 pp. for *Science*, August 1991.

Lumley, J. L. 1991. Review of: Acheson, D. J. 1990. *Elementary Fluid Dynamics*. Oxford, UK: Clarendon. 397 pp. and Chorin, A. J. & Marsden, J. E. 1990 *A Mathematical Introduction to Fluid Mechanics*. (Second Edition). Heidelberg: Springer. 168 pp. for *Physics Today*, November 1991.

Lumley, J. L. 1991. Some comments on research support. *Nonlinear Science Today* 1(2): 5-6.

Shih, T.-H. & Lumley, J. L. 1991 *A Critical Comparison of Second Order Closures with Direct Numerical Simulation of Homogeneous Turbulence*. NASA Technical Memorandum 105351/ICOMP-91-25/CMOTT-91-10. Lewis Research Center.

Stone, E. & Holmes, P. J. 1991. Unstable fixed points, homoclinic orbits and exponential tails in turbulence production. *Phys. Lett. A* 155: 29-42.

Papers submitted for publication

Berkooz, G., Elezgaray, J. & Holmes, P. 1991. Coherent structures in random media and wavelets. *Physica D*, Proceedings of NATO advanced research workshop *New trends in non--linear dynamics: non variational aspects*, to appear.

Berkooz, G., Holmes, P. & Lumley 1992. On the relation between low dimensional models and the dynamics of coherent structures in the turbulent wall layer. (submitted)

Berkooz, G., Holmes, P. & Lumley, J. L. 1992. Low dimensional models of the wall region in a turbulent boundary layer: new results. Proceedings of IUTAM Symposium and NATO Advanced Research Workshop on the Interpretation of Time Series from Nonlinear Mechanical Systems, Coventry, UK. *Physica D*, in press.

Berkooz, G., Holmes, P. & Lumley, J. L. 1992. On the relation between low dimensional models and the dynamics of coherent structures in the turbulent wall layer. *Journal of Fluid Mechanics*, to be submitted.

Berkooz, G., Holmes, P. & Lumley, J. L. 1993. The proper orthogonal decomposition in the analysis of turbulent flows. *Ann. Rev. of Fluid. Mech.* Vol. 25. To appear.

Berkooz, G., Holmes, P., Aubry, N. & Lumley, J. L. 1992. Observations regarding "Coherence and chaos in a model of the turbulent boundary layer"(by X. Zhou & L. Sirovich). *Physics of Fluids*, submitted.

Campbell, S. A. & Holmes, P. 1992. Heteroclinic cycles and modulated travelling waves in a system with D_4 symmetry. (submitted).

Cox, S. M. & Leibovich, S. 1991. Langmuir circulations in a surface layer bounded by a strong thermocline. *J. Phys. Ocean.* Submitted.

Leibovich, S. & Mahalov, A. 1991. On the calculation of coupling coefficients in amplitude equations . *J. Comp. Phys.* Accepted.

Leibovich, S. 1991. Spatial aggregation arising from convective activity. In *Patch Dynamics*, ed. S. Levin, T. Powell, and J. Steele, Berlin, etc.: Springer. To appear.

Leibovich, S., Cox, S., Moroz, I. M. & Tandon, A. 1991. Hopf bifurcation in Langmuir circulations. *Physica D*. Accepted.

Leibovich, S., Cox, S., Moroz, I. M. & Tandon, A. 1991. Nonlinear dynamics in Langmuir circulations with O(2) symmetry. *J. Fluid Mech.* Accepted.

Ristorcelli, J. R. & Lumley, J. L. 1992. A second order turbulence simulation of the Czochralski crystal growth melt: the buoyantly driven flow. *Journal of Crystal Growth*, under review.

<u>Reports</u>

Back, A., Guckenheimer, J. & Myers, M. 1992. *A Dynamical Simulation Facility for Hybrid Systems*. MSI Technical Report 92-6. Ithaca, NY: Cornell.

Berkooz, G. & Titi, E. 1991. The POD in systems with symmetry and harmonic analysis. To be submitted.

Berkooz, G. 1991. Statistical analysis of phase portraits: The case of limit cycles and their perturbations. To be submitted.

Berkooz, G. 1991. The metric structure and intrinsic homogeneity of turbulent systems with translational symmetry. In preparation.

Berkooz, G., Holmes, P. & Lumley, J. L. 1991. On the relation between low dimensional models and the dynamics of coherent structures in the turbulent wall layer". Submitted.

Guckenheimer, J. & Johnson, S. 1992. Beyond hyperbolicity: expansion properties of one-dimensional mappings. Preprint.

Ristorcelli, J. R. & Lumley, J. L. 1991. Turbulence simulations of the Czochralski melt, part 1: the buoyantly driven flow. Report No. FDA-91-04. Sibley School of Mechanical and Aerospace Engineering. Ithaca, NY: Cornell.

Awards, honors, new responsibilities

Holmes, P. Appointed Charles N. Mellowes Professor of Engineering, Cornell University 1992–

Holmes, P. Graduiertenkolleg Lecturer, Universität Stuttgart, June 1991.

Holmes, P. Advisory Committee of l'Institut des Sciences Mathématiques, Montréal, 1991–

Holmes, P. Rufus Bowen Lecturer, Department of Mathematics, University of California at Berkeley, October 1991.

Outside lectures

Berkooz, G. Jan 91 Cornell Dynamics Seminar - "On a recent paper of Ornstein and Weiss on the statistical analog of structural stability".

Berkooz, G. Mar 91 Cornell Transition and Turbulence Seminar - "The POD, Gevrey regularity and intermittency of dissipation in turbulent flows".

Berkooz, G. May 91 Cornell Dynamics Seminar - "Recent results concerning the POD".

Berkooz, G. Nov 91 APS/DFD meeting Scottsdale Az. - "Applications of symbolic dynamics to turbulent flows".

Berkooz, G. Oct 91 University of Paris VII math dept. - "Low dimensional models for the turbulent wall layer and dimension reduction".

Berkooz, G. Oct 91 University of Stuttgart Math institute A- "Low dimensional models for the turbulent wall layer and dimension reduction".

Berkooz, G., Elezgaray, J. & Holmes, P. 1991. *DARPA/ONERA Workshop on Wavelets and Applications*, Princeton, June 1991. (to appear). Coherent structures in random media and wavelets.

Berkooz, G., Holmes, P. & Lumley, J. L. 1991. *IUTAM Symposium and NATO Advanced Research Workshop on the Interpretation of Times Series from Nonlinear Mechanical Systems*, August 25-30, 1991. Low Dimensional Model of the Wall Region in a Turbulent Boundary Layer: New Results.

Holmes, P. & Berkooz, G. 1991. Abstracts of the *AFOSR Workshop on the Theory and Applications of Nonlinear Control*, Washington University, St. Louis, MO, August 15-16, 1991, pp. 52–57. Intermittent Dynamics in the Wall Layer: A Challenge for Nonlinear Control.

Holmes, P. 1992. *34th British Theoretical Mechanics Colloquium*, Keele University, U.K. March 30-April 2. Symmetry, Global Dynamics and Intermittency.

Holmes, P. Applied Science Colloquium, Harvard University, February 13, 1991. "Dynamical Systems and Turbulence: News from the Front."

Holmes, P. Mathematics Department, University of North Carolina, March 20th, 1991. "Dynamical Systems and Turbulence: News from the Front."

Holmes, P. Mathematisches Institut A, Universität Stuttgart, Germany, June 3-20th, 1991. A nine hour course "From Mechanics to Dynamical Systems and Back".

Holmes, P. Max-Planck-Institut für Strömungsforschung, Göttingen, Germany, June 13th, 1991. "Dynamical Systems and Turbulence: News from the Front."

Holmes, P. Systems Research Center, University of Maryland, April 18-19th, 1991. "Unstable Fixed Points, Heteroclinic Cycles and Exponential Tails in Turbulence Production."

Leibovich, S. 1991. Dynamics of resonant interactions in rapidly rotating pipe flow" (with A. Mahalov). 44th Ann. meeting of the Div. of Fluid Dyn.of the Amer. Phys. Soc., Phoenix, Nov.24-26, 1991. *Bull. APS*, **36**, 2666, Nov. 1991.

Leibovich, S. 1991. "Langmuir circulations in a surface layer bounded by a strong thermocline", (with S. Cox) 44th Ann. meeting of the Div. of Fluid Dyn.of the Amer. Phys. Soc., Phoenix, Nov.24-26, 1991. *Bull. APS*, 36, 2657, Nov. 1991.

Leibovich, S. 1991. Lehigh University, April 12, 1991, invited.

Leibovich, S. 1991. "Multiple bifurcations with O(2) symmetry in Langmuir circulations" (with S.M. Cox and I.M. Moroz). 44th Ann. meeting of the Div. of Fluid Dyn.of the Amer. Phys. Soc., Phoenix, Nov.24-26, 1991. *Bull. APS*, **36**, 2666, Nov. 1991.

Leibovich, S. 1991. Summer School on "Patch Dynamics in Terrestrial, Marine, and Freshwater Ecosystems, Cosponsored by NSF, DOE, NYS Sea Grant, and the Woods Hole Oceanographic Institutions. Held at the Mathematical Sciences Institute, Cornell/Invited

Lumley, J. L. & Berkooz, G. Control of the turbulent boundary layer. AFOSR Contractors' Meeting, Ohio State, April 1, 2, 3. Invited.

Lumley, J. L. Four lectures at Università degli Studi di Roma "La Sapienza" Dipartimento n. 37 - Idraulica, Trasporti e Strade: The turbulent boundary layer; Drag Reduction; Coherent Structures; and A low dimensional model of the wall region. Rome, Italy, May 20-24, 1991. Invited.

Lumley, J. L. Low dimensional model of the wall region in a turbulent boundary layer: new results, at the IUTAM Symposium and NATO Advanced Research Workshop on the

Interpretation of Time Series from Nonlinear Mechanical Systems, 25-30 August, 1991, University of Warwick, Coventry, UK. Invited.

Lumley, J. L. Stability, drag reduction and control of the turbulent boundary layer, using a low-dimensional model. Presented at the 13th IMACS World Congress on Computation and Applied Mathematics, July 22-26, 1991, Trinity College, Dublin, Ireland. Invited.

Poje, A. & Lumley, J. L. Coherent structure - fine grain turbulence interaction. Paper No. BA 1, *Bulletin of the American Physical Society* 36(10): 2627. 44th Annual Meeting, Division of Fluid Dynamics, American Physical Society, Scottsdale, AZ, 24-26 November 1991. Contributed.

Ristorcelli, J. R. & Lumley, J. L. A rapid pressure model frame indifferent in the 2D limit. Paper No. HA 6, *Bulletin of the American Physical Society* 36(10): 2687. 44th Annual Meeting, Division of Fluid Dynamics, American Physical Society, Scottsdale, AZ, 24-26 November 1991. Copntributed.

Professional Activities

Guckenheimer, J. 1991. Editorial Boards: Physica D, SIAM Review, Aequationes Mathematicae, International Journal of Bifurcation and Chaos

Guckenheimer, J. 1991. Director, Center for Applied Mathematics

Guckenheimer, J. 1991. Director of Research Programs, Cornell Theory Center

Guckenheimer, J. 1991. Advisory Board, The Geometry Center (Minnesota)

Holmes, P. CRM Special Year in Dynamical Sytems, Montréal, Quebec, 1993–94; co-organizer.

Holmes, P. MSRI Special Semester in Dynamical Systems and Probabilistic Method for PDE, Spring, 1994; Organizing committee member.

Holmes, P. Editorial Board Member: *Archive for Rational Mechanics and Analysis; Journal of Nonlinear Scinece/Nonlinear Science Today; Proc. Math. Society of Edinburgh.*

Holmes, P. Refereeing Activities: AMS Journals, Applied Mathematical Modelling, Automatica, Communications in Mathematical Physics, Ergodic Theory and Dynamical Systems, Handbook of Acoustics, Icarus, Journal of Applied Mechanics, Journal of Differential Equations, Journal of Dynamic Systems and Control, Journal of Fluid Mechanics, Journal of Mathematical Biology, Journal of Sound and Vibration, Lecture notes on Biomathematics, Mechanics Research Communications, Nonlinearity, Nonlinear Phenomena (Physica D), Physics of Fluids, Physics Letters, Rocky Mountain Journal of Mathematics, The Royal Society Journals, Transport Theory & Statistical Physics.

Holmes, P. Reviewing activities: American Scientist, Applied Mechanics Reviews, Bulletin of the A.M.S., I.M.A. Journal, Journal of Applied Mechanics, Journal of Sound and Vibration, Physics Today, Physics World, Shock and Vibration Digest, SIAM Review.

Leibovich, S. 1991. Associate Editor, *Journal of Fluid Mechanics*

Leibovich, S. 1991. Chairman, Operations Committee, Basic Engineering Group Operating Board, ASME

Leibovich, S. 1991. Chairman, U. S. National Committee on Theoretical and Applied Mechanics. (3 year term).

Leibovich, S. 1991. Co-editor, ACTA MECHANICA

Leibovich, S. 1991. Member of Executive Committee and Chair of External Affairs Subcommittee, Division of Fluid Dynamics, Amer Phys Soc.

Leibovich, S. 1988-1992. Member, Congress Committee of the International Union of Theoretical & Applied Mechanics.

Leibovich, S. 1989-1994. Member, Editorial Board, Annual Reviews of Fluid Mechanics

Leibovich, S. 1993. Member, Scientific Committee, 2nd International Conference on Fluid Mechanics, Beijing.

Leibovich, S. 1993. Member, Scientific Committee, IUTAM Symposium on Stability of Nonparallel Flows, Potsdam.

Leibovich, S. 1991. Member, Timoshenko Medal Selection Committee, ASME

Leibovich, S. 1992. Member, United States Papers Selection Committee, International Congress of Theoretical and Applied Mechanics, Haifa, ISRAEL.

Leibovich, S. 1991. Member-at-large, Basic Engineering Group Operating Board, ASME

Leibovich, S. 1991. NSF, Committee of Visitors, Fluid Dynamics, Hydraulics, and Particulates Programs, Division of Chemical and Thermal Systems

Leibovich, S. 1991. Reviewer: Journal of Fluid Mechanics, Physics of Fluids, Journal of Physical Oceanography, NSF

Lumley, J. L. Representative of Division of Fluid Dynamics, American Physical Society to U. S. Congress. Congressional Day, Thursday, April 25.

Lumley, J. L. Chairman, Ad-Hoc Planning and Advocacy Group for Turbulence.

Lumley, J. L. Editor and Chairman, Editorial Committee, Subcommittee on Research Directions in Fluid Mechanics, U. S. National Committee, Theoretical and Applied Mechanics.

Lumley, J. L. Member, Scientific Committee, IUTAM Symposium Eddy Structure Identification in Free Turbulent Shear Flows, Poitiers, France, September 14-16, 1992.

Lumley, J. L. Member, Advisory Committee, 8th Turbulent Shear Flows Symposium.

Lumley, J. L. Chairman, Advisory Committee, Center for Turbulence Research, Stanford, NASA Ames.

Lumley, J. L. Chairman, Technical editorial board, *Izvestiya: Atmospheric and Oceanic Physics*.

Lumley, J. L. Co-editor, *Annual Reviews of Fluid Mechanics*.

Lumley, J. L. Editor, *Theoretical and Computational Fluid Dynamics.*

Lumley, J. L. Member, editorial board *Fluid Mechanics: Soviet Research.*

Lumley, J. L. Session Chairman, Conference on Turbulence Modeling, NASA Lewis, August 21, 22.

Lumley, J. L. Reviewer, *J. Fluid Mech., Phys. Fluids, Physics Letters A, Combustion Science & Technology, AIAA J, Int. J. of Multiphase Flow, J. Sci. Instrum.*, NSF, ARO

Lumley, J. L. Expert witness, Breed Automotive (Plaintif) vs. David Breed. Analysis of air bag sensor.

Lumley, J. L. Expert witness, Philosopher's Wool Co. (Plaintif) vs. Ontario Hydro. Evaluation of Hydrogen Sulfide monitoring stations installed by Ontario Ministry of the Environment.